

# On estimating the total number of intermediate mass black holes

Daniel P. Caputo,<sup>★</sup> Nathan de Vries, Alessandro Patruno and Simon Portegies Zwart<sup>★</sup>

*Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

Accepted 2016 December 20. Received 2016 December 20; in original form 2014 October 17

## ABSTRACT

Black holes have been detected with masses less than  $10^2$  and greater than  $10^5 M_\odot$ , but black holes with masses in the intermediate range are conspicuously absent. However, recent estimates of the mass of HLX-1, currently the strongest intermediate mass black hole (IMBH) candidate, suggest an approximate mass of  $10^4 M_\odot$ , and recent estimates of the mass of M82 X-1 suggest a mass of  $4 \times 10^2$ , placing them within the missing black hole range. This raises the question of whether these are unique objects or if many more of these objects should be expected. We estimate the number of HLX-1 like IMBHs expected within the distance of 100 Mpc to be within an order of  $\approx 10^6$ , or  $\approx 10^2$  IMBHs within a galaxy, and about two orders of magnitude more when considering less massive IMBHs using M82 X-1 as a prototype. In the process of estimating this value, we determine the form of the mass function within the sphere of influence of a newly formed IMBH to be a power law with a slope of  $-1.83$ . Furthermore, we find that we are only able to fit both the period and luminosity of HLX-1 with a stellar companion with a mass between  $\approx 10$  and  $11 M_\odot$ , a result that is fairly robust to the mass of the IMBH between  $10^3$  and  $10^5 M_\odot$ .

**Key words:** methods: numerical.

## 1 INTRODUCTION

It is generally accepted that both stellar mass and supermassive black holes have been definitively detected in large numbers. Intermediate mass black holes (IMBHs), on the other hand, have never been detected with such certainty and even the strong candidates are few in number (Gladstone 2013). Moreover, there has been a long history of IMBH candidates turning out to be other, less exotic, objects (e.g. Baumgardt et al. 2003; Schödel et al. 2005). There are indeed several IMBH candidates, but still definitive proof and precise measurements of their mass elude the community (Greene & Ho 2004). In this letter, we estimate the number of IMBHs in the local universe, based on the assumption that IMBHs do in fact exist, that the two strongest IMBH candidates are representatives of the yet unknown population of IMBHs, and that all the X-ray outburst from suspected IMBHs are the result of mass transfer directly from stars in orbit around the IMBH that are overflowing their Roche lobe (Portegies Zwart, Dewi & Maccarone 2004; Kaaret & Feng 2007; Lasota et al. 2011).

The benefit of estimating the size of a hereunto unknown population of IMBHs is in understanding the expectation of observing additional IMBHs in the future. If IMBHs are plentiful, then they will play an important, and interesting, role in the evolution of galaxies (Ebisuzaki et al. 2001). In that case, it will be important to seek out these objects to fully understand their role, and doing so

will require carefully constructed experiments and observation time on telescopes to carry out those experiments. If, however, IMBHs are indeed very rare, could the few examples simply be ‘failed’ supermassive black holes, were IMBHs the seeds of the current supermassive black holes? In this case, theorists will need to work hard to understand why Nature, while so willing to allow for both its small and truly massive brethren, is stingy with these middle-child black holes.

Currently the strongest IMBH candidate is HLX-1. Though there are other suggestions about its true nature (King & Lasota 2014), its very unusual properties give it the strongest chance of being an IMBH. M82 X-1 is also a strong IMBH candidate, with mass estimates ranging from 10’s of  $M_\odot$  to  $10^3 M_\odot$ . For this work, we will consider HLX-1 and M82 X-1 as the only bona fide ultraluminous X-ray source IMBHs observed to date.

## 2 OBSERVATIONAL CONSTRAINTS HLX-1 AND M82 X-1

Ultraluminous X-ray sources are defined as being extranuclear in location and having an X-ray luminosity in excess of  $10^{39} \text{ erg s}^{-1}$  (Roberts 2007). Farrell et al. (2009) identified a unique, extranuclear source in the edge-on spiral galaxy ESO 243-49 with a peak-to-peak X-ray luminosity in excess of  $10^{42} \text{ erg s}^{-1}$ . Using the term coined by Gao et al. (2003), hyperluminous X-ray source (HLX), Farrell et al. (2009) called this object HLX-1. Based on the nature of HLX-1, they suggested that it was the premier IMBH candidate. Mass estimates for HLX-1 have ranged from  $>500 M_\odot$  (Farrell et al. 2009), to

<sup>★</sup> E-mail: [caputo@strw.leidenuniv.nl](mailto:caputo@strw.leidenuniv.nl) (DPC); [spz@strw.leidenuniv.nl](mailto:spz@strw.leidenuniv.nl) (SPZ)

between  $9.2 \times 10^3$  and  $9.2 \times 10^4 M_\odot$  (Webb et al. 2012), and to between  $6.3 \times 10^3$  and  $1.9 \times 10^5 M_\odot$  (based on modelling of the accretion disc while varying the spin of the hole; Straub et al. 2014). After continued observations, Webb et al. (2012) showed a very regular X-ray outburst frequency of once per year, although the most recent outbursts have been delayed (Godet et al. 2014; Kong, Soria & Farrell 2015). The peak luminosity of HLX-1 corresponds to an accretion rate of  $4 \times 10^{-4} M_\odot \text{ yr}^{-1}$  (assuming a disc radiation efficiency of 0.11; Godet et al. 2012). Wiersema et al. (2010), using H $\alpha$  emission, found HLX-1 to be at a redshift consistent with ESO 243-49, and placed HLX-1 inside ESO 243-49, at a distance of 95 Mpc.

Another IMBH candidate, M82 X-1, is located 5.2 Mpc away (Liu & Bregman 2005), with a peak-to-peak X-ray luminosity of  $7.6 \times 10^{40} \text{ erg s}^{-1}$  and 62-d period (Kaaret & Feng 2007; Kaaret, Feng & Gorski 2009), and a mass between  $\approx 3 \times 10^2$  and  $3 \times 10^3 M_\odot$  (Mucciarelli et al. 2006; Pasham, Strohmayer & Mushotzky 2014), though a few estimates place its mass as low as  $\approx 20 M_\odot$  (Dewangan, Titarchuk & Griffiths 2006; Okajima, Ebisawa & Kawaguchi 2006).

### 3 METHODS

In order to estimate the number of IMBHs in the local universe, we construct something like a Drake equation for IMBHs that we estimate from the probability of detecting such objects. This probability is based on the likelihood of a star of a given mass orbiting the black hole, the length of time that star would be transferring enough mass to produce an X-ray flux above the background, and the probability of detecting such an object given the sensitivity and sky coverage of the observatory. The number of observed IMBHs can thus be described as

$$N_{\text{obs}} = N_{\text{IMBH}} \times N_{\text{mass transfer}} \times P_{\text{detection}}. \quad (1)$$

We find the number of IMBHs by solving for  $N_{\text{IMBH}}$ :

$$N_{\text{IMBH}} = \frac{N_{\text{obs}}}{N_{\text{mass transfer}} \times P_{\text{detection}}}, \quad (2)$$

where  $N_{\text{IMBH}}$  is the number of IMBHs,  $N_{\text{obs}}$  is the number of IMBHs observed as ULXs and we assume currently this is limited to HLX-1 and M82 X-1.  $N_{\text{mass transfer}}$  is the average number of stars that an IMBH will have in an orbit such that the star could overflow its Roche lobe (RLOF) and thus able to transfer mass on to the hole. Extrapolating from a linear fit of the simulation data of Blecha et al. (2006), we find that a  $10^3$  and  $10^4 M_\odot$  black hole should have, on average, 2.2 and 19.6 stars, respectively, in a mass transferring orbit over the duration of their simulations (100 Myr).  $P_{\text{detection}}$  is dependent on the coverage of X-ray data on the sky, and the probability that the system is in an ‘active’ state. But different stellar masses have different active times so we must scale the probability a system is active by the probability that a given mass would be present around an IMBH, i.e. using the normalized mass function found around the black hole; that is

$$P_{\text{detection}} = F_{\text{sky}} \int_{M_{\text{min}}}^{M_{\text{max}}} P_{\text{active}} \times P_{\text{mass|mass function}} dm. \quad (3)$$

The likelihood of finding the star-black hole system in an active state, i.e.  $P_{\text{active}}$ , is the fraction of the star’s lifetime spent transferring mass above a given rate. Because the star is transferring mass, its evolution and lifetime are altered and so we must perform stellar evolution simulations of stars that are losing mass via RLOF.

In Section 3.1, we provide more details about the simulations we perform. We convert the measured mass transfer rate to an X-ray luminosity, using a 10 per cent efficiency rate and assuming that all of the mass lost from the star is accreted on to the black hole, and then we calculate the fraction of time spent over a given luminosity.  $P_{\text{mass|mass function}}$  is measured from data taken from simulations of IMBH formation via collision run away (Fujii, Saitoh & Portegies Zwart 2012). Measurement of this value is addressed at length in Section 3.2.

Lastly, thanks to the *ROSAT* All-Sky Survey, we have nearly full-sky coverage, with the caveat being that there are many unidentified sources, some of which could be unknown IMBHs, this is complicated even further by the transient nature of these objects. However, we will assume that the sky coverage is complete, i.e.  $F_{\text{sky}} = 1$ , because it is beyond the scope of this work to determine the fraction of objects that would be strong IMBH candidates (see Sutton et al. 2012, for an example of attempts to identifying possible candidates). This is of course a simplification and it may result in an underestimated value.

### 3.1 Mass transfer

In order to measure the fraction of time a star of a given mass would spend transferring mass to its IMBH companion to the total age of the star,  $P_{\text{active}}$ , we have run stellar evolution models of stars as they transfer mass to an IMBH. We have used a stellar evolution code and numerical methods to model a star in orbit around an IMBH wherein we vary the mass of both the IMBH and stars, as well as the eccentricity of the orbit. The star is placed on an orbit with a given eccentricity and its semimajor axis is allowed to grow such that it is always just over flowing its Roche lobe at pericentre, it is then evolved, using the *AMUSE* framework (Portegies Zwart et al. 2012; Pelupessy et al. 2013), with the stellar evolution code *MESA* (Paxton et al. 2011). At every step of the evolution, the amount of mass transfer,  $\dot{m}$ , from the star to the IMBH is calculated based on the analytical prescription described below and that mass-loss is provided to the stellar evolution code that adjust the evolution accordingly. With such models, we determine the time spent transferring mass above a certain rate, the lifetime of the star given this mass-loss rate, and if such a model could produce a system as described in Lasota et al. (2011).

We calculate the mass-loss from the donor by solving equation 1 in Portegies Zwart et al. (2004) that provides a calculation for the change of the semimajor axis,  $\dot{a}$ , based on the effects of gravitational radiation, Roche lobe overflow and mass-loss via stellar wind. For our calculations, we neglect the wind and assume that the mass in the system is conserved, then solving for  $\dot{m}$  we find

$$\dot{m} = \left( \frac{\dot{a}}{a} - \frac{64}{5} \frac{G^3}{c^5} \frac{m_* m_\bullet m_t}{a^4} \right) / \left( \frac{2}{m_*} - \frac{2}{m_\bullet} \right), \quad (4)$$

where  $a$  and  $\dot{a}$  are the semimajor axis and its time derivative, respectively;  $G$  and  $c$  are the gravitational constant and the speed of light in vacuum, respectively; and finally  $m_*$ ,  $m_\bullet$  and  $m_t$  are the masses of the donor star, the black hole and the total system mass, respectively.

Our simulations are very similar to those found in Patruno et al. (2005), Madhusudhan et al. (2008) and Patruno & Zampieri (2008), the primary difference being that we calculate the mass-loss from the donor via the methods in Portegies Zwart et al. (2004) for  $\dot{m}$  and then evolve the companion in a stellar evolution code to which we provide the mass-loss rate we have calculated. The secondary difference between our method and those of the previous works is

that we calculate the size of the Roche lobe with a correction for the eccentricity of the orbit based on equations 51 and 52 of Sepinsky, Willems & Kalogera (2007). Even with these two differences, our work agrees well with the previous work.

From these simulations, we calculate the mass transfer per unit time, i.e. the luminosity, and the orbital period of the star around the black hole.

### 3.2 Mass function

In order to calculate the probability of a star being in orbit around an IMBH,  $P_{\text{mass}}|_{\text{mass function}}$ , we must first know how the stellar masses are distributed, i.e. the mass function near the black hole. We perform these calculations, using two different mass functions. First, we calculate the probability of a star of a given mass orbiting a black hole by using a Salpeter mass function (Salpeter 1955) with masses between 1 and 100  $M_{\odot}$ . This generic stellar mass distribution yields a probability distribution function of

$$\text{PDF}_{\text{SP}} = 1.35 \times M^{-2.35}, \quad (5)$$

where  $M$  is the mass of the star in units of  $M_{\odot}$ .

The second mass function we used is derived from  $N$ -body simulations by Fujii et al. (2012). In their set of simulations, stars were allowed to collide and merge, which in some cases resulted in a collision runaway, producing very massive stars of up to about 500  $M_{\odot}$ . Upon their death stars of such a mass would produce an IMBH (Portegies Zwart & van den Heuvel 2007). Portegies Zwart & McMillan (2002) suggested this method for IMBH formation. Fujii et al. (2012) have provided a successful test of this possible formation theory. In that work, they used the Salpeter function as their initial mass function, but after 3 Myr the mass function near the black hole had changed dramatically with a larger fraction of high-mass stars near the black hole than the Salpeter function would have predicted. As we will mention later, this has a dramatic effect on the number of predicted IMBHs, and we speculate that the careful choice of a realistic mass function will have a similarly profound impact on the results of other studies. But the significance for this work lies in being able to measure the distribution of stellar masses near a newly formed IMBH. (This is based on the assumption that IMBHs form via collision runaway, other formation mechanisms may produce different mass functions.) By deriving the mass function from a self-consistent  $N$ -body simulation of collision runaway, we are able to produce a much more realistic mass function for what might be found around an IMBH. We used the data from when the cluster was  $\approx 3$  Myr old, as that corresponds to when the very massive star would collapse into an IMBH (Portegies Zwart et al. 1999). We find that a power law of the form:

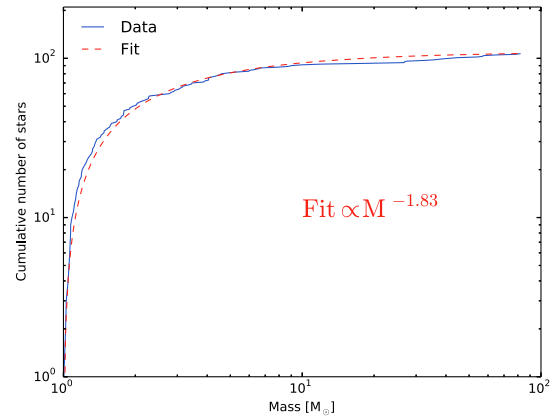
$$M^{-1.83}, \quad \text{for } 1 M_{\odot} \leq M \leq 75 M_{\odot} \quad (6)$$

describes this more realistic mass function for the stars in the sphere of influence of the black hole in these simulations (see Fig. 1). From this, we obtain a probability distribution function of:

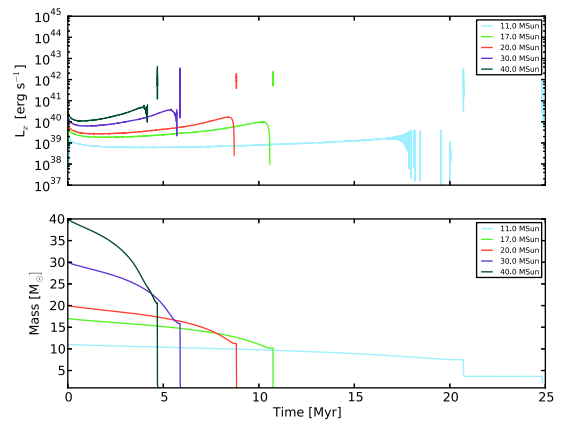
$$\text{PDF} = 0.85 \times M^{-1.83}. \quad (7)$$

## 4 RESULTS AND DISCUSSION

In Fig. 1, we have plotted the stellar mass function in the sphere of influence of an IMBH just after formation via collision runaway. The solid blue line plots the cumulative number of stars as a function of mass, and the dashed red line plots the fit to the data. We find that the best fit is a power law with a slope of  $-1.83$ .



**Figure 1.** The cumulative number of stars as a function of mass. The red dashed line is the fit to the data (solid blue line). The fit is a power law with a slope of  $-1.83$ .



**Figure 2.** The mass and X-ray luminosity as a function of time. The top panel shows the X-ray luminosity, while the bottom panel shows the mass for five different initial masses as shown in the legend.

We have run stellar evolution simulations of stars transferring mass to black holes with masses of  $10^3$ ,  $10^4$  and  $10^5 M_{\odot}$  with 17 different stellar masses between 4 and 40  $M_{\odot}$  and orbital eccentricities of 0.7, 0.8, 0.9, 0.95 and 0.99. Fig. 2 is a plot of the stellar mass (bottom panel) and corresponding X-ray luminosity due to mass accretion on to the black hole (top panel). The mass of the black hole is  $10^4 M_{\odot}$  and the orbital eccentricity is 0.99. For clarity, we have only plotted five different initial stellar masses of the 17 such simulations we ran for all black hole masses and eccentricities we examined.

From Fig. 2, we note that the average X-ray luminosity increases with initial stellar mass. However, the peak luminosity is more consistent; we find a dramatic increase in luminosity at the end of the star's luminosity curve. This results from these stars going through a giant stage, quickly growing the stellar radius and so a large amount of mass falls outside of the Roche lobe at pericentre. This can be seen in the bottom panel of Fig. 2 with the sudden mass-loss at the same time. After this impressive mass-loss, the star's envelope remains well within the Roche lobe and so there is generally no more mass-loss. For initial masses less than or equal to 11  $M_{\odot}$  this can, but does not always, happen a second time though generally with a lower luminosity. The peak luminosity,  $\approx 10^{42} \text{ erg s}^{-1}$ , is fairly constant for these events, with only a weak dependence on initial mass. We find these results hold regardless

of black hole mass and orbital eccentricity, but that is partially due to our assumptions that all of the mass lost from the star falls on to the black hole and that we do not allow the orbit to circularize. Allowing the orbit to circularize would have a limited effect because mass transfer rates are only very weakly related to the eccentricity of the orbit in our approximation (see e.g. equation 4).

#### 4.1 The mass of HLX-1's companion

Though we have not plotted it here, we also determine the evolution of the associated orbital period for all the simulations. If our aim were to reproduce HLX-1 data, using a Lasota et al. (2011) like model, with the added constraint of its roughly 1 yr period, we find only a relatively small range of initial stellar masses, between 10 and 11  $M_{\odot}$ , that can produce the observed peak luminosity and the period simultaneously. This mass estimate is less than the turnoff mass of the young cluster around HLX-1 based on the age estimate from Soria et al. (2012) and is in line with the turnoff mass from the age estimate of Farrell et al. (2012), 6 and 13 Myr, respectively. This would exclude both sets of results that suggest a companion mass of either  $\approx 2$  or 20  $M_{\odot}$ .

#### 4.2 The number of IMBHs

Using the stellar evolution simulations, the mass function near a newly formed IMBH and equation (2), we find that there should be  $\approx 10^6$  black holes like HLX-1 within 100 Mpc. If these were to be distributed uniformly throughout that volume, we would expect  $\approx 1$  IMBHs per cubic Mpc; however, these objects will be preferentially found in and around galaxies. Using Gourgoulhon, Chamaraux & Fouque (1992), we estimate  $\approx 10\,000$  galaxies within that volume and assuming that IMBHs are equally distributed amongst all galaxies, we predict  $\approx 100$  such IMBHs per galaxy. Of course, if these numbers are dramatically wrong, it would suggest that, for example, our mass transfer model is wrong or that HLX-1 is not an IMBH.

Applying the same methods to M82 X-1, we find there should be  $\approx 10^6$  M82 X-1 black holes within 22 Mpc (the distance at which M82 X-1 would be observable at the same level as HLX-1). Assuming a constant IMBH density, we extrapolate that there should be  $\approx 10^8$  of these lower mass IMBHs within 100 Mpc. Again using the 10 000 galaxies from Gourgoulhon et al. (1992), we estimate there should be  $\approx 10^4$  M82 X-1 like black holes within an average galaxy.

While  $10^4$  may seem large, if IMBH masses are distributed along a continuum it does not seem unreasonable that there would be, for example, many more  $5 \times 10^2 M_{\odot}$  IMBHs than  $10^4 M_{\odot}$  IMBHs (such as HLX-1). An additional concern may be where to harbour so many objects; globular clusters seem to be a natural place to find such objects and with about 160 globular clusters in our Galaxy our prediction for the number of more massive objects, i.e. the  $\approx 100$  which are HLX-1 like, would, as an order of magnitude estimate, fit neatly within the number of globular clusters.

The lower mass,  $10^2$ – $10^3 M_{\odot}$ , IMBHs could form, via collision runaway, and reside in young clusters as suggested in van den Heuvel & Portegies Zwart (2013), who also claim the signature of the formation of these IMBHs would be superluminous supernovae (SLSNe). Assuming SLSNe always produce an IMBH, we can estimate IMBH numbers from the number of SLSNe. Gal-Yam (2012) provides a rate for SLSNe of  $10^{-8} \text{ Mpc}^{-3} \text{ yr}^{-1}$ , giving:

$$10^{-8} \text{ Mpc}^{-3} \text{ yr}^{-1} \times 10^{10} \text{ yr} \times (10^2 \text{ Mpc})^3 = 10^8 \text{ SLSNe} \quad (8)$$

**Table 1.** The estimated number and total mass of SMBHs, IMBHs, StMBHs and Stars within the Milky Way (left two columns) and within 100 Mpc (right two columns).

	In Milky Way		Within 100 Mpc	
	Number	$M_{\text{total}}(M_{\odot})$	Number	$M_{\text{total}}(M_{\odot})$
SMBH	1	$4 \times 10^6$	$10^4$	$10^{11}$
IMBH	$10^4$	$10^8$	$10^8$	$10^{12}$
StMBH	$10^8$	$10^9$	$10^{11}$	$10^{12}$
Stars	$10^{11}$	$10^{11}$	$10^{15}$	$10^{14}$

within the age of the Universe and out to a distance of 100 Mpc. Perhaps surprisingly, this second method, using a physically unrelated model, serendipitously agrees with the results we found using the method outlined above. Additionally, we note that van den Heuvel & Portegies Zwart (2013) suggest that these events, and hence IMBHs, are not equally distributed amongst galaxies but rather they find that the Milky Way is expected to underproduce these events by a factor of  $10^2$  compared to compact blue galaxies. This means the number of lower mass IMBHs in the Milky Way could be as low as  $10^2$ .

As these young clusters evaporate, if they evaporate, their IMBHs would be left with at most only the few stars within the IMBH's sphere of influence. If there are such low-mass IMBHs threading their way through the Milky Way then *Gaia* may provide a unique opportunity to spot them.

As *Gaia* (de Bruijne 2012) observes a billion or so stars in the Milky Way, making very high-precision measurements of the peculiar motion of the stars, it should observe some systems for which their motions can only be explained with the addition of an IMBH. However, if there are in fact only  $10^2$  such IMBHs in the Milky Way, and *Gaia* is only sampling 1 out of every  $10^2$  stars in the Milky Way, we would expect to detect on order of 1 of these objects. Of course, as with the rest of this letter, caution must be taken when considering such a low number of statistics.

The spatial distribution of these systems should not deviate much from their initial distribution, at least not as a result of dynamical friction since for the  $10^3 M_{\odot}$  case dynamical friction should only result in an inward migration of the black hole of  $\approx 40$  pc, and only  $\approx 0.4$  kpc even for a  $10^5 M_{\odot}$  black hole in 13 Gyr (assuming a value of 6 for the Coulomb logarithm). Additionally, the all-sky, X-ray survey provided by *eROSITA* (Merloni et al. 2016), with an anticipated launch data in 2016, will likely provide many more IMBH candidates with its sensitivity and long expected exposure time.

#### 4.3 IMBHs in relation to other black holes

Finally, in Table 1 we compile the number and total mass of different types of massive objects [stars, stellar mass black holes (StMBHs), IMBHs and SMBHs] in both our Galaxy and within a sphere with a radius of 100 Mpc. Here, we outline how we arrived at these values: in the Milky Way there is one observed SMBH, Sgr A\*, with a mass of  $4.1 \times 10^6 M_{\odot}$  (Ghez et al. 2008). Caramete & Biermann (2010) estimate a total number of SMBHs within 100 Mpc with masses  $> 10^7 M_{\odot}$  to be about  $2.4 \times 10^4$  and from the mass density provided therein, we estimate a total mass of  $2.8 \times 10^{11} M_{\odot}$  within the same volume. We must be careful to note that while the number of SMBHs within 100 Mpc may be larger due to excluding the SMBHs with masses  $< 10^7$ , Caramete & Biermann (2010) claim that the total mass is barely dependent on the cutoff due to a flattening of the integral mass function at lower mass.



In this work, we have calculated the values for the number of IMBHs within 100 Mpc and within the Milky Way. In order to estimate the total mass of the IMBHs, we used the estimated mass data of Moran et al. (2014) and find an average IMBH mass of  $\approx 6.7 \times 10^3 M_\odot$  and we assume this value for both within 100 Mpc and the Galaxy. The data in Moran et al. (2014) regard only nuclear IMBHs while we have examined off-nuclear IMBHs; it is unknown if such populations may be related, e.g. off-nuclear IMBHs may be the post-merger product of their host galaxy and a dwarf galaxy where it had been a nuclear IMBH, however if such populations would be unrelated this mass estimate may be incorrect. To find the number of StMBHs, we estimate that approximately 1 out of every 1000 stars in a Kroupa mass function (Kroupa 2001) is massive enough ( $>20 M_\odot$ ) to produce an StMBH at the end of their life, and Özel et al. (2010) provided an estimate of typical Galactic StMBH to be  $7.8 M_\odot$  – again we assume this value is valid within 100 Mpc in addition to the Milky Way. The number of stars in the Milky Way is  $\approx 3 \times 10^{11}$  and we measure the average stellar mass from a Kroupa mass function to be  $\approx 0.4 M_\odot$  for a total mass of  $1.2 \times 10^{11} M_\odot$ . To find the number of stars within 100 Mpc, we take the stellar mass density from Dickinson et al. (2003) and find a total stellar mass of  $4 \times 10^{14} M_\odot$ , continuing to use an average stellar mass of  $0.4 M_\odot$ , we then find  $1 \times 10^{15}$  stars. We find an ideal fit of the number of black holes versus mass, using a power law of the form:

$$N = 4.95 \times 10^9 M^{-1.47}, \quad (9)$$

where  $N$  is the number and  $M$  the average black hole mass.

## 5 CONCLUSION

We have determined the stellar mass function within the sphere of influence of a newly formed IMBH to be of the form  $M^{-1.5}$ . This mass function combined with the fraction of time a star is transferring mass to the black hole, the probability that an IMBH would have a star in an orbit that it could transfer mass via RLOF, and the number of IMBHs observed allows us to estimate the number of IMBHs within 100 Mpc (the distance to HLX-1). We find that within 100 Mpc, there should be of the order of  $10^8$  IMBHs, the majority being M82 X-1 like ( $10^2$ – $10^3 M_\odot$ ) with only  $10^6$  being HLX-1 like ( $10^4 M_\odot$ ). This translates into  $\approx 10^4$  IMBHs within each galaxy in that volume, assuming that they are equally distributed amongst  $10^4$  galaxies. The uncertainty in our estimation is dominated by our assumptions (e.g. that IMBHs exist in this current epoch, that HLX-1 and M82 X-1 are such IMBHs and are representative of a larger population, that ULX IMBHs are powered by RLOF and there are not more than a few other RLOF powered IMBHs currently in an active state, etc.) that make estimating the error a bit artificial; if, for example, the mass is not being accreted via RLOF or HLX-1 and M82 X-1 are not IMBHs then our model is not able to estimate this population. However, if there is dramatically more than an order of magnitude of unidentified RLOF powered IMBHs within the flux limits of current surveys then we could have underestimated the number. Due to these difficulties, we estimate the error to be at least an order of magnitude. We are hopeful that results from *Gaia* and the upcoming X-ray mission *eROSITA* (Merloni et al. 2016) will help to clarify many of these outstanding questions and perhaps identify IMBHs through dynamical means.

As an unexpected result, we found that a simultaneous fit to the mass-loss and apparent period of the star overflowing its Roche lobe to HLX-1 was only possible in our simulations with a companion mass between 10 and  $11 M_\odot$ . This is also in line with the turnover

mass based on the age estimate of the young cluster around HLX-1. However, this mass estimate would exclude a suggestion that the companion is 2 or  $20 M_\odot$ .

Finally, we show in Table 1 how our results of expected number of IMBHs compare to other estimates of numbers and mass of stars, StMBHs and SMBHs in our Galaxy and within 100 Mpc. We find that the number and total mass in IMBHs that we predict seem to fit well within these ranges. Fitting the number of black holes versus mass with a power law, we find  $N = 4.95 \times 10^9 M^{-1.47}$  produces a fit with an  $R^2$  value of 1.0.

## ACKNOWLEDGEMENTS

We are very grateful to Michiko Fujii for providing us with her data, as well as Alex Rimoldi and Edwin van der Helm for their thoughtful comments. This work was supported by the Netherlands Research Council (NWO grant numbers 612.071.305 (LGM), 614.061.608 (AMUSE) and 639.073.803 (VICI)) and by the Netherlands Research School for Astronomy (NOVA).

## REFERENCES

- Baumgardt H., Makino J., Hut P., McMillan S., Portegies Zwart S., 2003, *ApJ*, 589, L25
- Blecha L., Ivanova N., Kalogera V., Belczynski K., Fregeau J., Rasio F., 2006, *ApJ*, 642, 427
- Caramete L. I., Biermann P. L., 2010, *A&A*, 521, A55
- de Bruijne J. H. J., 2012, *Ap&SS*, 341, 31
- Dewangan G. C., Titarchuk L., Griffiths R. E., 2006, *ApJ*, 637, L21
- Dickinson M., Papovich C., Ferguson H. C., Budavári T., 2003, *ApJ*, 587, 25
- Ebisuzaki T. et al., 2001, *ApJ*, 562, L19
- Farrell S. A., Webb N. A., Barret D., Godet O., Rodrigues J. M., 2009, *Nature*, 460, 73
- Farrell S. A. et al., 2012, *ApJ*, 747, L13
- Fujii M. S., Saitoh T. R., Portegies Zwart S. F., 2012, *ApJ*, 753, 85
- Gal-Yam A., 2012, *Science*, 337, 927
- Gao Y., Wang Q. D., Appleton P. N., Lucas R. A., 2003, *ApJ*, 596, L171
- Ghez A. M. et al., 2008, *ApJ*, 689, 1044
- Gladstone J. C., 2013, *Mem. Soc. Astron. Ital.*, 84, 629
- Godet O. et al., 2012, *ApJ*, 752, 34
- Godet O., Lombardi J., Antonini F., Webb N. A., Barret D., Vingless J., Thomas M., 2014, *ApJ*, 793, 105
- Gourgoulhon E., Chamaraux P., Fouque P., 1992, *A&A*, 255, 69
- Greene J. E., Ho L. C., 2004, *ApJ*, 610, 722
- Kaaret P., Feng H., 2007, *ApJ*, 669, 106
- Kaaret P., Feng H., Gorski M., 2009, *ApJ*, 692, 653
- King A., Lasota J.-P., 2014, *MNRAS*, 444, 30
- Kong A. K. H., Soria R., Farrell S., 2015, *Astron. Telegram*, 6916
- Kroupa P., 2001, *MNRAS*, 322, 231
- Lasota J.-P., Alexander T., Dubus G., Barret D., Farrell S. A., Gehrels N., Godet O., Webb N. A., 2011, *ApJ*, 735, 89
- Liu J.-F., Bregman J. N., 2005, *ApJS*, 157, 59
- Madhusudhan N., Rappaport S., Podsiadlowski P., Nelson L., 2008, *ApJ*, 688, 1235
- Merloni A. et al., 2016, *LPN*, 905, 101
- Moran E. C., Shahinyan K., Sugarman H. R., Velez D. O., Eracleous M., 2014, *AJ*, 148, 136
- Mucciarelli P., Casella P., Belloni T., Zampieri L., Ranalli P., 2006, *MNRAS*, 365, 1123
- Okajima T., Ebisawa K., Kawaguchi T., 2006, *ApJ*, 652, L105
- Özel F., Psaltis D., Narayan R., McClintock J. E., 2010, *ApJ*, 725, 1918
- Pasham D. R., Strohmayer T. E., Mushotzky R. F., 2014, *Nature*, 513, 74
- Patruno A., Zampieri L., 2008, *MNRAS*, 386, 543
- Patruno A., Colpi M., Faulkner A., Possenti A., 2005, *MNRAS*, 364, 344

- Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, *ApJS*, 192, 3
- Pelupessy F. I., van Elteren A., de Vries N., McMillan S. L. W., Drost N., Portegies Zwart S. F., 2013, *A&A*, 557, A84
- Portegies Zwart S. F., McMillan S. L. W., 2002, *ApJ*, 576, 899
- Portegies Zwart S. F., van den Heuvel E. P. J., 2007, *Nature*, 450, 388
- Portegies Zwart S. F., Makino J., McMillan S. L. W., Hut P., 1999, *A&A*, 348, 117
- Portegies Zwart S. F., Dewi J., Maccarone T., 2004, *MNRAS*, 355, 413
- Portegies Zwart S., McMillan S., Pelupessy I., van Elteren A., 2012, in Capuzzo-Dolcetta R., Limongi M., Tornambè A., eds, *ASP Conf. Ser. Vol. 453, Advances in Computational Astrophysics: Methods, Tools and Outcome*. Astron. Soc. Pac., San Francisco, p. 317
- Roberts T. P., 2007, *Ap&SS*, 311, 203
- Salpeter E. E., 1955, *ApJ*, 121, 161
- Schödel R., Eckart A., Iserlohe C., Genzel R., Ott T., 2005, *ApJ*, 625, L111
- Sepinsky J. F., Willems B., Kalogera V., 2007, *ApJ*, 660, 1624
- Soria R., Hakala P. J., Hau G. K. T., Gladstone J. C., Kong A. K. H., 2012, *MNRAS*, 420, 3599
- Straub O., Godet O., Webb N., Servillat M., Barret D., 2014, *A&A*, 569, 116
- Sutton A. D., Roberts T. P., Walton D. J., Gladstone J. C., Scott A. E., 2012, *MNRAS*, 423, 1154
- van den Heuvel E. P. J., Portegies Zwart S. F., 2013, *ApJ*, 779, 114
- Webb N. et al., 2012, *Science*, 337, 554
- Wiersema K., Farrell S. A., Webb N. A., Servillat M., Maccarone T. J., Barret D., Godet O., 2010, *ApJ*, 721, L102

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.